André Marie Ampère (1775-1836)

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This year we celebrate the 150th anniversary of the birth of electromagnetism and the classic experiments of Ampère. This, coupled with the fact that there exists very little record in the English language of the life and work of this great scientist of the nineteenth century, seems a sufficient reason for writing this article.

Ampère the boy

André Marie Ampère was born on January 20th, 1775 in Lyons, the old Roman capital of Gaul. His father, Jean Jacques Ampère, was a merchant and a Justice of the Peace. Thus the first seven years of André's life was spent amongst the bustle of his father's activities in Lyons. This was soon to change for a quieter life when the family retired to their country estate at Poleymieux.†

André's informal education began under the guidance of his father. Up to the age of 13 his studies were mainly literary. He read avidly but with great systematic care. An example of this was the selfimposed task of reading through the 22 volumes of the *Encyclopedia* of d'Alembert and Diderot in strict alphabetical order! His father would supplement this kind of study with conversations during their long walks in the countryside.

It wasn't long before the modest library of the retired merchant showed its insufficiency. Already the boy had shown a keen interest in arithmetic but had found difficulty with the mathematical sections of the *Encyclopedia*. Thus, from time to time, he would go with his father to Lyons where he had the chance to talk to the Abbé Daburon, an able mathematician from the Trinity College of Theology. André confided to him that he didn't understand the *d*'s in the calculus! With inspiration from the friendly teacher and a

Figure 1 *André Marie Ampère* (Photo: Deutsches Museum, München).

†The former Ampère home at Poleymieux, about 8 miles north up the river Saône from Lyon, is now an Electricity Museum. It is maintained by the *Société des Amis d'André Maire Ampère* who have their headquarters at 5 place Jules–Ferry, Lyon. (6e).

measure of success with Rivard's *Elements of Mathematics* he continued on to more advanced work such as the treatise of La Chapelle and the Marquis de l'Hôpital on conic sections. The Abbé led him on to the works of Bernoulli and Euler for which he had to learn Latin. By the age of 18 he had worked through the two great treatises of that epoch, Laplace's *Traité de Mécanique* and Lagrange's *Mécanique Analitique*.

Ampère the young man

The years of learning spent in the idyllic surroundings of Poleymieux suddenly changed. Those were troubled times and Ampère's father was caught up in the political net of the French Revolution. Lyons, having great silk mills which supplied the Royal Courts of Louis XVI tried to remain Royalist. So when the political trouble spread from Paris to Lyons Ampère's father, as judge, dealt with the agitators of the Revolution.

After a calm the Revolution started up again. This time a group of assailants were commissioned to take Jean Ampère because of his earlier decisions as judge. He was caught and sent to the scaffold. On the day of his execution he wrote to his wife saying 'My biggest spending has been the buying of books and geometry instruments which our son could not do without for his instruction; but this spending has even been a wise economy since he has never had another teacher other than himself' (Hoefer 1859). He wrote further '. . . Say nothing to Josephine (his daughter) of the unhappy fate . . . As to my son, *I expect everything of him*' (Arago 1873, p116).

The mental stress and anguish which fell on André did the opposite to his father's wishes. One whole year of his life seems to have remained a blank. He was numbed by the catastrophe and spent months mechanically passing the time. Strangely it was through the botanical letters of Rousseau that Ampère repaired his mind for study. He now gave little thought for mathematics but instead engrossed himself in the works of Linnaeus and other botanists.

At 24, Ampère married Julie Carron, a neighbour's daughter. The responsibilities of marriage threw extra burdens on his meagre means and it was not long before he took up a teaching post to earn some money. The school was the fourteenth century Ecole Centrale (now Lycée Lalande) at Bourg-en-Bresse. The forty miles between himself and his wife was just too much to bear and so he returned to Lyons the following year.

Changing teaching posts was not the easy matter it is today. Any such change had to be justified to the authorities and a professorship had to be won by writing a kind of dissertation. Most of Ampère's spare time at Bourg was taken up in writing such a dissertation and it was on the popular subject of gambling. This was finally presented before Lalande at the *Académie Royale des Sciences* of the *Institut de France* on January 12, 1793. Lalande was already an old man and had lost his taste for this sort of thing. Several other scholars examined it but few understood it. However, after making one or two minor corrections, Delambre persuaded Bonaparte, then first consul, to elect Ampère to a mathematics post at the Lycée in Lyons. All this went well, and with a great deal of relief, Ampère was reunited with his family—but not for long. Julie, who had been ill for some time, died in the summer of 1803.

Once more a dark cloud hung over this young man. In his depressed state of mind – perhaps with memories of his father's fate – he decided to leave Lyons in order to continue his career in Paris.

The early Paris period

Ampère, now 30, started life afresh in the stimulating Parisian atmosphere. Once again he submitted a mathematical paper to the *Insitut* in order to attract the attention of Lagrange and Delambre. And so, by October 1803 he had obtained a post of assistant teacher of calculus at the 'new' *Ecole Polythechnique*. At first he engrossed himself completely in his teaching and in metaphysics. His students often mocked him for his dreadful taste in clothes and his poor blackboard work. Even so he had to take on extra teaching to pay off some debts he had with Fresnel.

Although he did manage to return to Poleymieux from time to time, he was a lonely man and had begun to contemplate remarriage. His melancholy at that time was noticeable by the letters he wrote to his intimate friends, the chroniclers, Ballanche and Brédin, in Lyons. Nevertheless the following year was more successful academically. His teaching post was elevated to that of 'reserve' teacher of calculus and he became a member of the Bureau Consultatif des Arts et Métiers. Through a new contact, Dégerande (secretary to Napoléon), Ampère was put in touch with the Potot family. Seemingly Ampère was blind to the dishonesty of the Potots and foolishly he married the Potot daughter who turned out to be cruel, callous and as dishonest as her parents. The marriage soon became intolerable but because of his religion any divorce was out of the question.

Interest in chemistry

Eventually Ampère was separated from his wife in 1809. After this he succeeded in getting his mother

and sister to sell the Poleymieux estate in order that they could live with him in Paris. It was not long after this that his mother died and from this time he seems to have delved more and more into the scientific advances of that epoch. It was the discovery of potassium by Davy that initiated his interest in chemistry. As soon as he heard of the news he sent off a letter of congratulation to Davy in which he also expressed his sympathies with him against the phlogistic ideas of the old school. This was the beginning of many years of correspondence between them (Gardiner 1965, 235–245). In one letter Ampère, by then eager to have his name known amongst English scientific society, told Davy of Dulong's discovery of nitrogen trichloride. Davy, remembering what Ampère had earlier requested, mentioned his name when he gave a report on the new discovery to the Royal Society in 1813. In effect Davy had published Dulong's discovery first; thus breaking the unwritten scientific rule by which Dulong should have had the privilege to publish first. The outcome of all this was a great deal of embarrassment for Ampère. Nevertheless, their correspondence continued to flourish, especially that concerning the similar properties of fluorine, bromine and iodine.

There is no room here to go into details of Ampère's chemistry but it is interesting to know that he occupied a good deal of his time in studying the gas laws. He had his own notions on atoms which ran contrary to the Daltonian viewpoint. Ampère's atoms were physical points which had attractive and repulsive properties. This meant that it took at least four atoms to make a molecule. It was using these strange notions that he arrived at what we would call Avogadro's law, but well in advance of Avogadro's publication. He also sought to explain Mariotte's (Boyle's) law using his atomic theory but he did have some difficulty in reconciling Gay Lussac's law with his simple notions. These chemical studies temporarily ceased at the beginning of 1814 when a colleague died and he was therefore burdened with extra teaching. Today we have records of his views in chemistry through his correspondence on these matters with his Lyonaise friends, Ballanche and Brédin, as well as with Davy. (Launay 1925, 147–193).

In the period 1801–1813, besides the interests he showed in the discovery of new elements, Ampère produced three mathematical papers which added to his prestige. The two calculus treatises he wrote in 1813 secured him a place, left vacant by the death of Lagrange, at the *Institut*. In the same year he was made a member of the Légion d'Honneur. He now justified his place amongst the learned gentlemen by producing two more papers; one on Mariotte's (Boyle's) law (1814) and the other on the laws of refraction (1815). His great essay *On the Natural Classification of Simple Bodies* (1816) was the result of all his chemical studies over the previous years (Gay Lussac and Arago 1816a, b). This work alone would require a separate study and assessment but indeed reflects the whole chemical knowledge of that epoch.

We now see this phase in Ampère's life as the beginning of a more stable existence. Louis XVIII had done much to heal the wounds of the Revolution and so many of the political tensions, easily sensed by those who lived in Paris, subsided. This, coupled with the fact that he had bought a small house close by the *Jardin Botanique* for his sister and himself, made him relatively happy. His joy was further increased a few years later when his son, Jean Jacques, left his aunt Carron's custody in order to study philosophy in Paris.

The impossibility of electromagnetism

Before we can begin to look at the work for which we, as physicists, remember Ampère we must first take a look at some of the ideas which were the precursors of that epoch. It was Newton's law of gravitation of 1687 that gave the eighteenth century scientists an impetus to look for a law of electric and a law of magnetic attraction and repulsion. Electric and magnetic phenomena were first clearly distinguished by Gilbert in his *De Magnete* (1600) and since then the two phenomena were studied separately. The eighteenth century scientists also concerned themselves with the nature of the two phenomena. Various hypotheses were advanced to show the two fluid nature of electricity (such as the *vitreous* and *resinous* fluids of Du Fay in 1734 and the *affluent* and *effluent* streams of the Abbé Nollet in 1745) or the single fluid nature (such as proposed by Watson in 1746 and separately by Franklin in 1747). Likewise there existed corresponding hypotheses on the nature of magnetism (such as Brugman's and Wilcke's *boreal* and *austral* magnetic fluids in 1957 and Aepinus's one fluid hypothesis of 1759). In the second half of the eighteenth century scientists such as Priestley and Michell suspected that the law of attraction and repulsion in both magnetism and electricity would be that of an inverse square law. This was borne out by the classic experiments of Coulomb in 1785.

Just before Coulomb published his investigations the confusion over the origins of electric and magnetic fluids was so strong that the *Bavarian Academy of Sciences* offered a prize for the best paper on the analogous properties of electricity and magnetism.

The results of this venture were published in 1784 by J H Swinden who concluded that the phenomena were essentially different (Pearce Williams 1962). Likewise, Coulomb insisted that the two phenomena were not related. With these emphatic 'conclusions' no further attempts were made to relate electricity and magnetism. This denial of any relation between the two seems to have hung over into the nineteenth century, despite the invention of the voltaic pile. Even Ampère was guilty of keeping these two branches of science apart during his early lectures at the École Central in Bourg.

The discovery of electromagnetism

On September 4th, 1820, at one of the Monday meetings of the *Académie Royale des Sciences* of the *Institut de France*, Dominique François Jean Arago (1786–1853) made a brief announcement which was to alter the course of the private studies of many members of that learned body of gentlemen. In the winter months of 1819, Hans Christian Oersted, (1777–1851), professor at Copenhagen, had made an accidental discovery that magnetism could be produced from 'galvanism'. He had noticed that a compass needle close by a galvanic circuit was turned at right angles when the circuit was complete. Oersted clearly understood the importance of his discovery and he was certain it would create a great deal of rethinking on the hypotheses of the previous century. Thus when he published his account on July 26th, 1820, he did so in Latin for he knew that valuable time would be lost if he wrote in his native tongue (Gay Lussac and Arago 1820a). Soon after the translation into French the Genevois physicist, August de la Rive, repeated Oersted's experiment in front of a few guests. One of the witnesses was Arago and it was his announcement and demonstration at the following Monday meeting of the *Institut* that hastened so many members into their own researches.

The spate of material discovered, reported and published in Gay Lussac's and Arago's *Annales* was so overwhelming that we are often confused nowadays as to who should be credited with what. In those volumes of the early 1820's we find the studies of Ampère, Arago, Berthollet, Berzellius and Biot as well as occasional reports and letters of Faraday and Davy from the *Royal Institution.*

Identification of magnetism as electricity

September 18th 1820

From hearing the announcement, Ampère had not wasted any time in putting his mathematical and practical skills to work. On this date he read a memoir in which he reduced Oersted's discovery to two general facts: (i) a magnetic compass needle could be attracted or repelled by a current in an adjacent wire, and (ii) all magnetic phenomena were due to electrical effects alone.

September 25th, 1820

It was at this meeting that Ampère set out the main points of his theory (see table 1). Ampère had confirmed point (i) before this meeting by experiment. From point (iii) we can deduce that he did not believe in 'action at a distance' for the 'new' electricity. Point (iv) was a reiteration of a general fact announced at the previous meeting. Ampère inserted point (ix) merely to remove any confusion which might have arisen for his colleagues in confusing the magnetic effects with Volta's electric tension.†

These nine points were all realized experimentally within a few weeks. We can catch something of Ampère's excitement over his work by the following extract from a letter written to his son who was then living in Geneva (See figure 2): 'All my time has been taken up by an important circumstance in my life. Since I first heard of the wonderful discovery of M.

Table 1 The nine principles of Ampère's electromagnetic theory

(i) Two currents attract if they travel in the same sense and repel if they travel in opposite senses.
(ii) Two current carrying wires, restrained to move in parallel planes, tend to draw each other into a parallel position such that the current is in the same direction.
(iii) Attractions and repulsions are absolutely different from those of ordinary (static) electricity.
(iv) Magnets are merely assemblages of electric currents produced by the action of the particles of steel on each other.
(v) Currents in a magnet circulate in the opposite sense to the apparent movement of the Sun if the magnet rested in its natural position due to the Earth's magnetism.
(vi) Other known effects between magnets can be explained in terms of (v).
(vii) The action between the Earth's magnet can be explained by supposing there to be electric currents running east–west due to the Earth's magnet.
(viii) There is no difference between the poles of a magnet except that the electric current which gives rise to the magnetic properties exists in the opposite senses.
(ix) Volta's explanation of the two electricities, positive and negative, of the two extremities of a pile which obeyed Coulomb's law, did not explain the origin of the magnetic fluids.

†We must not forget that Oersted did try to explain what he had discovered. He was essentially a follower of the 'two fluid' hypothesis and so believed that the compass needle deflections were due to 'conflicts' between the opposing agencies.

Oersted . . . of the action of galvanic currents on a compass needle, I have never stopped thinking about it; I have written a general theory on this phenomena and the ones already known and have tried all the experiments indicated by the theory, all of which have succeeded and have taught me as many new facts. I have read the beginning of a summary at the meeting of the *Institut* eight days ago. On the following days, once with Fresnel, once with Desprets, I made confirmatory experiments. I repeated these all Friday evening at Poisson's . . . in front of some students from the École Normale. They all succeeded; but the experiment I planned as decisive proof required two galvanic piles. Being tried with two weak piles at Fresnel's, it did not succeed. At last yesterday I obtained permission from Dulong to allow Dumotier to sell me the big pile that he was building for his physics course at the Faculty and which was just finished. This morning, the experiment has been done at Dumotier's with good success and repeated today at 4 o'clock at the meeting of the Institut. No one objected to my new magnetic theory . . . which explains all galvanic phenomena. This does not resemble anything said until now. Tomorrow I will re-explain this to M. de Humboldt, and the day after, to M. de Laplace at the Bureau des Longitudes.' (Launay 1925, p196).

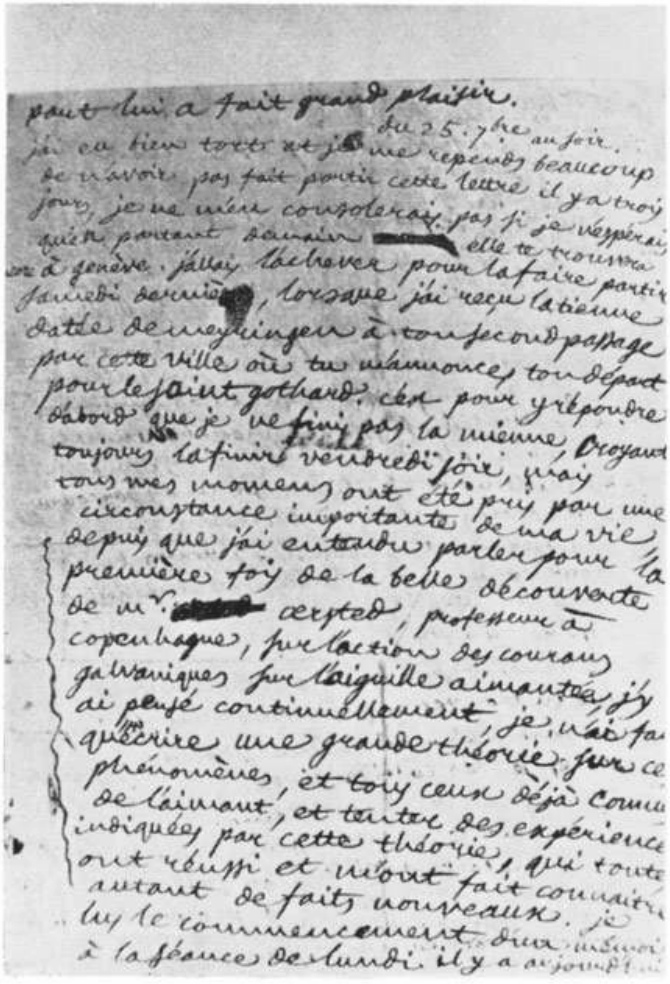

Figure 2 Part of a letter from Ampere to his son, dated 25 September 1820.

October 2nd, 1820

The details of Ampère's verbal announcement were presented in a paper presented to the *Institut* entitled *Concerning the Mutual Action between two electric currents, between an electric current and a magnet or the Earth's globe, and between two magnets* and this was ultimately published in the *Annales*. (Gay Lussac and Arago 1820b).

In this paper he discussed how the two sorts of electricity travelled, first quickly accelerating and then levelling out to a constant velocity due to the inertia of the fluids, and how, after attaining a kind of equilibrium against each other, an *electric tension* arose. It was also in this paper that he decided to adopt a convention for the direction of flow of the electricity. He wrote '. . . I shall understand every time that the question arises, to avoid tedious repetition, after the words *sense of the electric current* these words *of positive electricity*; so that if we are considering, for example, a voltaic pile, the expression *direction of the electric current in the pile* will designate the direction from the end where hydrogen is disengaged in the decomposition of water to that where oxygen is obtained . . .' (Magie 1965, p450). However disagreeable this convention may now be in the light of the invention of the electron, one cannot help but appreciate Ampère's logical approach to a very mysterious subject.

Up until now the only electrical measuring instrument was the electrometer which measured tension. Ampère had quickly spotted that the simple deflection of a magnetic needle was sufficient to measure and indicate the intensity of an electric current. To distinguish it from the electrometer he called it a *galvanometer*.

The parallel wire experiment mentioned in his letter to his son was also described in this first memoir. By this time he had made a much more convenient arrangement of the experiment. Basically the apparatus was composed of two parallel wires of which CD could move (because of the pendulum suspension) and AB was fixed. The necessary connections were made by means of the mercury cups at R, S, T and U as shown in figure 3 (upper).

This memoir is particularly fascinating because not only do we have the early statements, definitions, inventions and experiments by which Ampère made his name, but we also find that Morse was not the inventor of the magnetic telegraph. Ampère wrote 'Following up the success of the experiment which was

suggested to me by the Marquis de Laplace, by employing as many conducting wires and magnetized needles as there are letters, by fixing each letter on a different magnet, and by using a pile at a distance from these needles, . . . we may form a sort of telegraph, by which we write all the matters we may wish to transmit, across whatever obstacles there may be, to the person whose duty it is to observe the letters carried by the needles.' Of course Morse's system was more convenient because it did not need so many wires and the code invented speeded up the process as only one tapping key was needed.

October 9th, 1820

Following up the previous experiment on parallel wires Ampère introduced a new arrangement. This time the moveable wire NM was restricted to move in a plane parallel to the fixed wire AB and at all times maintain a common perpendicular PZ as shown in figure 3 (lower). The connections were made by means of the mercury cups. For current flowing in the same directions, say A to B and N to M, the arrangement remained as shown. But, when the current was reversed in NM the wire rotated so that currents in like senses were restored. The experiment was then repeated by fixing a bar magnet in the housing, Z, but no current in the wire AB. The effect was the same as before. Ampère explained that '. . . if we conceive one of these currents as set up at every point of a line drawn on the surface of a magnet from one pole to the other, in planes perpendicular to the axis of the magnet, then from the simple comparison of facts it seems to me impossible to doubt that there are really such currents about the axis of a magnet . . .'. However, Ampère did qualify that these magnetic currents were incapable of creating any chemical effects if the magnet was placed in a liquid.

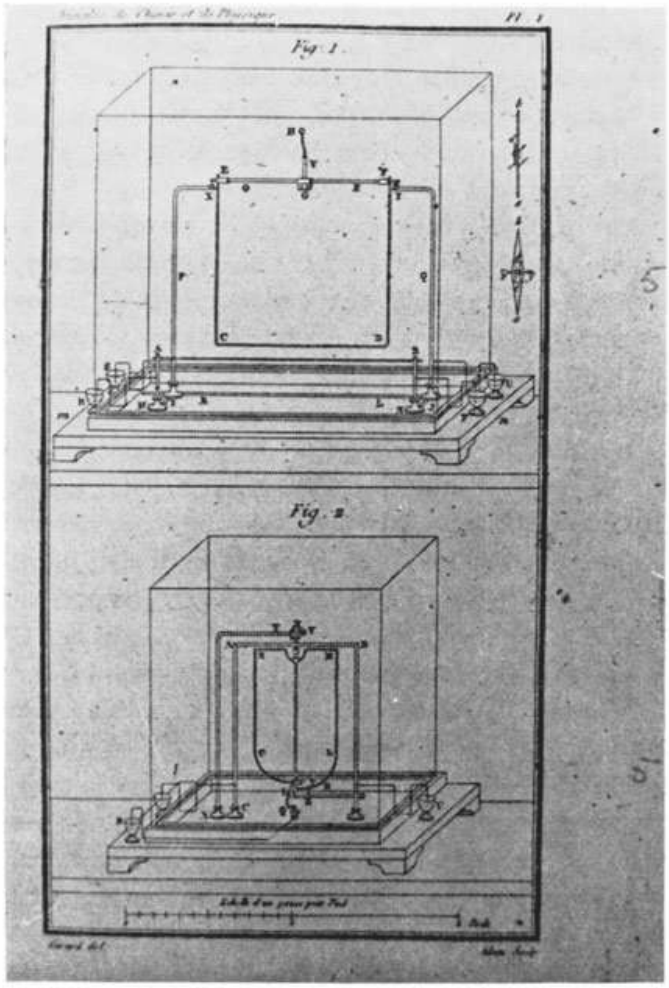

Figure 3 Two forms of the parallel wire experiment.

October 16th, 1820

Ampère read a note to the *Institut* members about Arago's discovery that a bar of steel placed in a helically wound coil would become magnetized. (Gay Lussac and Arago, 1820c). This *electrodynamic solenoid*, as he later termed the arrangement, he regarded as final evidence for his hypothesis.

October 30th, 1820

This meeting not only heard Ampère's persistent reiteration that all magnet phenomena were due solely to electric currents but that the Earth's magnetism could be used to demonstrate his hypothesis. For this he used the instrument shown in figure 4 (lower). The apparatus was placed in the magnetic meridian and a current passed round the wire. The indicating needle, in the plane of the wire frame, rotated to a direction at right angles to the direction of the Earth's lines of force. He also exhibited at this meeting the instrument shown in figure 3 (lower).

November 6th, 1820

Following up Arago's work with a coil wound in a helix, Ampère stated that a coil could be 'likened unto a magnet'. To demonstrate this he wound such a coil on the outside of two glass tubes in the manner shown in figure 4 (upper). The suspended arrangement acted just like a bar magnet and came to rest in the magnetic meridian. He even went on to suggest that this arrangement might well make a portable instrument with which to measure electric currents.

Attempts at a law of force

October 9th, 1820

Many scientists of the day would have been quite satisfied in getting as far as Ampère; he had produced a molecular theory and had clearly demonstrated that magnetism was a sort of 'galvanism' – but not Ampère – he was a mathematician! He now announced his intention to find a law of attraction and repulsion between infinitestimally small elements of a current carrying wire – a task which was to draw on his knowledge of calculus.

October 30th, 1820

The meeting had started by Ampère demonstrating some more of his apparatus. Immediately after this his rival in this field, Jean-Baptiste Biot (1774–1862), from the Collège de France read a paper on his work in this field. Biot was one year older than Ampère but he had led a much more interesting and varied career up to this time. Now Biot had left behind his optics, crystallography and physics of the atmosphere, in order to turn his attentions to the new mystery of electromagnetism. With his junior teacher, Felix Savart (1791–1841), he had been occupied in finding a quantitative expression for the field at some point from a straight current carrying wire. To do this they measured the oscillations of a bar magnet at various distances from the wire (a technique developed earlier by Coulomb and which we now recognize as the 'oscillating magnetometer' method). What they found was stated thus; 'From the point where the molecule resides, that is a point in the magnet; draw a perpendicular to the axis of the wire. The force which acts on the molecule is perpendicular to this line and to the axis of the wire. Its *intensity is reciprocal to the simple distance*' (the italics are mine) (Gay Lussac and Arago 1820d).

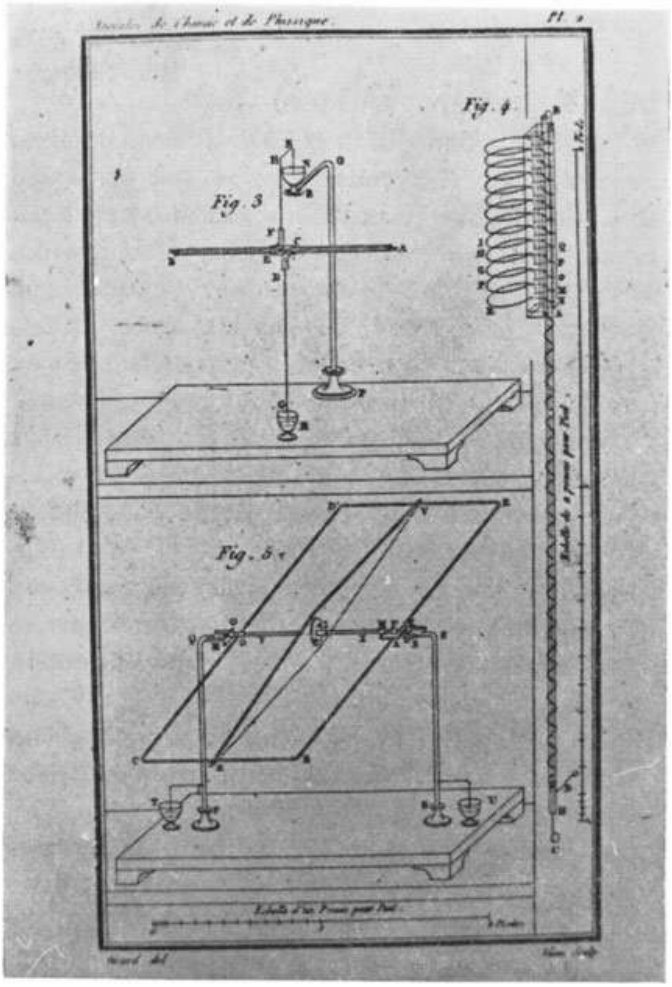

Figure 4 Two constructions in which current carrying conductors behave like compass needles.

November 6th, 1820

Biot had got a head start on Ampère in that he had already found a law of force but Ampère was much more methodical in his approach to the matter. When Ampère had announced that Arago's solenoid could be likened unto a magnet he admitted to the members that he had not found a law of force for the arrangement. At this meeting he made some indication that this could be achieved if one was to consider the vectorial sum of all the effects due to individual elements of a solenoid at some point in space.

December 4th, 1820

Ampère worked on this problem for about a month and at this meeting made a public communication concerning his studies. He explained that the law of force would be of the inverse square type like that of 'ordinary' electricity and gravitation and also that it would depend on the angles made between the elements chosen and the line joining their middles.

With regard to Biot's experiment and the law deduced mathematically from this by Laplace, Ampère showed that this could be deduced also from the principles stated in his memoir on October 9th. However, for the purpose of the general proof he considered the action between two elements carrying currents g and h in nonparallel wires. In his derivation he wanted to get away from the idea of magnetic particles of austral and boreal fluid of which they knew nothing but simply to consider the action of one current on another. The outcome of his argument was the expression

$$\frac{gh}{r^2}\left(\sin\alpha\sin\beta\cos\gamma+\frac{n}{m}\cos\alpha\cos\beta\right)$$

for the action between two such elements. See figure 5.

December 11th, 1820

Ampère now showed that the ratio n/m was small enough to be considered as zero, thus reducing the expression for the action between two elements to

$$\frac{gh\sin\alpha\sin\beta\cos\gamma}{r^2}$$

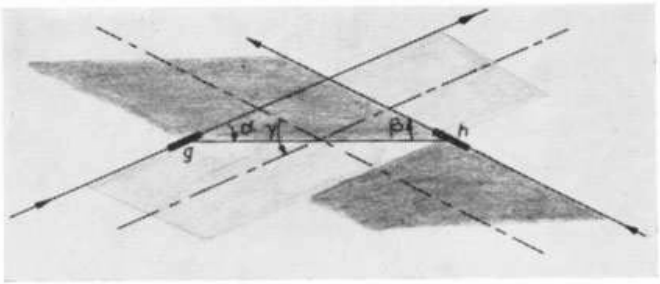

Figure 5 General case for the inverse square law between two current carrying elements.

He also gave an account of the analogy between this expression and that concerning the heat radiation between infinitesimally small areas.

December 26th, 1820

It was impossible for Ampère to test his expression directly, as infinitesimal portions of the conductor were involved. However, he did have one course of action left open to him and that was to assume the formula for various experimental arrangements and to show that equilibrium could be produced. In other words he was to use a null method which is now commonplace in this sort of work.

The following description relates to one of the four cases of equilibrium considered in his final treatise (Ampère 1827, 185ff). Referring to figure 6, HG is a portion of a double rectangular loop of wire free to move about a vertical axis. The current in the arrangement follows the path pabcdefgMABCDEFGHIKNhiklmnq. In particular the current flows up PQ and up RS and the effects of these repel HG such that HG comes to rest equidistant from the two vertical wires. In PQ is a straight wire bc and in RS the wire kl is twisted back and forth. Since the rest position of GH indicated that the action of RS was equivalent to that of a straight conductor then we may conclude, by considering kl to be made up of infinitesimal vertical and horizontal elements, that the effects of the horizontal elements of RS cancel. As Ampère had hoped, this suggested that the total action taken right round the closed circuit was zero due to the opposing forces or moments. (The effect of the Earth's magnetism was accounted for by making the suspension astatic).

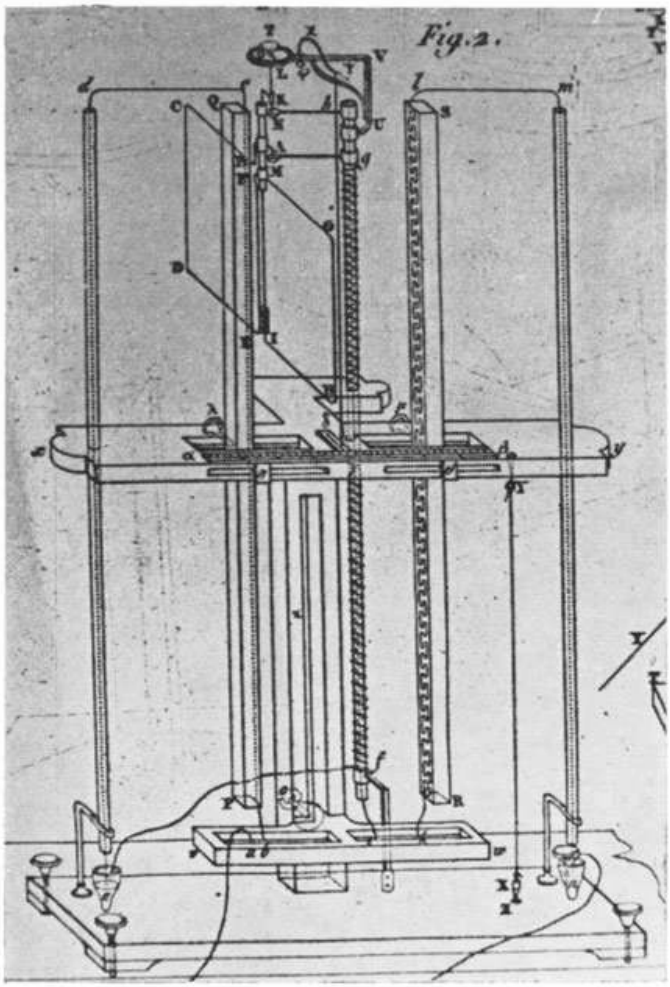

Figure 6 Apparatus for testing a particular case of equilibrium which was predicted by the inverse square law.

January 8th and 15th, 1821

The final phases of the mathematical proofs were the accounts on how to use the calculus with his formula for various cases. On the latter date he posed a question which indicated that he was not completely clear as to how the magnetic currents circulated. He wished to know if the closed currents which gave the steel its magnetic properties were either concentric around the axis joining the poles of the magnet or around each particle in planes perpendicular to the axis of the magnet. Quite rightly he explained that either hypothesis would account for the known phenomena. Without going into details of electron spin we also indicate the equivalence of these two systems of thought in our teaching today.

Unacceptability and jealousy

Within four months of starting his researches into electrodynamic phenomena Ampère had performed several distinct experiments, introduced a new terminology and had produced a theory of magnetism which seemed both mathematically plausible and practically agreeable. Now, having more or less achieved his aims, he began to rewrite all he knew on the subject for his *magnum opus*.

Unfortunately much of his spare time during 1821 was taken up in dealing with his critics. Some of his contemporaries tried to contradict his work and he also met with a certain amount of rebuff from England. Of his fellow countrymen Savary, Becquerel and Berzelius objected to his hypothesis and from across the Channel the members of the Royal Institution seemed very doubtful about the new ideas. On February 10, 1821, Davy wrote to Ampère '. . . several of the facts I have observed have led me to doubt the identity of electricity and magnetism' (Launay 1925, p199) although he gave no real grounds for this statement. Of Faraday's objections August de la Rive, in Geneva, blamed Faraday for not having made sufficient use of Ampère's experiments to which Faraday replied 'M. Ampère's experiments are excellent and his theory ingeneous; . . . being naturally

sceptical on philosophical theories I thought there was a great want of experimental evidence . . .' (Gardiner 1965, p 240). It was not just his scepticism but also, as he admitted to Ampère, his own insufficiency in mathematics. Faraday also thought of electricity as the passage of a force but for Ampère it was the passage of positive and negative fluids.

Now, in 1821 Biot brought out a second edition of his *Physique Experimentale* which was to take into account the new developments in electricity and optics. Nowhere in this did Biot claim he was the discoverer of the inverse square law (as many modern text books lead us to believe). He did, however, accredit this to Laplace who, he stated, '. . . deduced from our (Biot–Savart) observations, that the individual law of elementary forces exercised by each slice of the wire, was the ratio inversely as the square of the distance . . . ' (Biot 1821 2, p 122). Nevertheless, he claimed their law to be the *loi fundamentale* (Biot 1821 *1*, p xiii) and nowhere did he mention the labours of Ampère of which he was well aware. This is not surprising as there was a good deal of animosity on the part of Biot against Ampère and Arago at this time.

The jealous Biot made an open attack by attempting to show how Ampère had skillfully profited from Oersted's work. This resulted in not only Ampère being insulted but also his colleague, Arago, who was involved in the criticism. Infuriated by the lack of comprehension of his colleagues, Ampère wrote to Roux in Geneva and also the *Société Philomathique* setting down what was to be credited to himself and Arago.

Despite the set backs Ampère continued his writing and eventually produced an account entitled *The determination of the formula which represents the mutual action of two infinitely small portions of voltaic conductors* which was presented to the *Institut* on June 10th, 1822. In this account he used the more familiar form of the calculus, letting $g = i\mathrm{d}s$ and $h = i'\mathrm{d}'s$ so that the mutual action between the two elements of parallel wires was given by the expression

$$\frac{ii'\,\mathrm{d}s\,\mathrm{d}s'}{r^n}$$

where $n = 2$ and $\alpha = \beta = \pi/2$ and $\gamma = 0$.

By July Ampère was in great need of a break from his duties. The kindly *Ecole* authorities gave him a leave of absence so that he could take a holiday at his friend's in Lyons.

Related experiments

Whilst Ampère was resting in Lyons he wrote to de la Rive in Geneva. The outcome of this was that Ampère was invited to spend the first week in September in Geneva. During that week several new experiments were carried out. These tend to be ignored nowadays and yet one of them clearly shows that Faraday was not the discoverer of electromagnetic induction.

Professor Pictet in Geneva had loaned the two experimenters a large and strong horseshoe magnet. With this de la Rive and Ampère had *set out* to see if they could produce electricity by 'influence' – an experiment which Ampère had tried a year earlier but without success. However this time they found that when the magnet approached a thin copper ring the ring would be either attracted or repelled. From this Ampère concluded that electric currents are 'excited' in bodies near to which magnets pass. On returning to Paris Ampère communicated this new experience to the *Institut* on September 16th, 1822, and also to Brédin on September 24th, 1822 (Gay Lussac and Arago 1822b).

These experiments were later followed by Arago's work on electromagnetic damping (1824) and a similar experiment by Herschel and Babbage (1825). Although Ampère corresponded with Herschel and Babbage on this matter no further experiments of a quantitative nature were carried out and so it was left to Faraday to find the laws of electromagnetic induction (1831).

It was with some misgivings that Ampère wrote to de la Rive in April 1833 saying '. . . Unfortunately, neither you nor I even dreamed of analysing this phenomena . . .' (Cramer 1963) and again in a letter to de la Rive, dated November 8th, 1833, Ampère returned to the question of priority saying that 'It isn't Mr Faraday who is the originator of making of his own accord the production of a current by influence, since we obtained this current in 1822' (Cramer 1963).

Faraday, who had earlier expressed scepticism with regard to Ampère's hypothesis, produced a very ingeneous experiment which indeed helped to confirm Ampère's work! Perhaps it was de la Rive's earlier grumble that caused Faraday to carry out this experiment. Whatever the cause of the idea he sucessfully showed his wife, on Christmas Day 1821, that a magnet could be made to rotate around a current carrying wire. Faraday informed Ampère of his experiment and before the end of the following month Ampère had repeated the experiment but it was over a year before he decided to reply. In that reply, of April 18th, 1823, Ampère used his theory to account for several new facts. In addition he triumphantly pointed out to Faraday how the rotation of a magnet in mercury round the current carrying wire and the inverse effect fitted in with the predictions of his theory. (Gay Lussac and Arago 1823). Ampère had always

seemed confident in Faraday and had hoped that one day Faraday would accept his theory. Alas! Faraday never did accept Ampère's views fully. Nevertheless, Ampère continued to correspond with Faraday (and also Brewster in Scotland) until about 1825.

To fit in with the various new discoveries, Ampère presented the *Institut*, on December 22nd and 29th December 1823 and January 5th 1824, with a re-edited version of his earlier memoir *On the Mutual Action of Electric Currents* (Gay Lussac and Arago 1823b and 1824a). Looking through the *Annales* of this period it is impossible to find a volume without some mention of electrodynamic discoveries. Even Davy carried out an experiment, which he credited to Wollaston, which was thought to be of sufficient interest to have a translation of the account for the *Annales* (Gay Lussac and Arago 1824c). In this experiment he allowed electric current to enter and leave a mercury bath by means of two fixed vertical wires. As he approached the bath from above or below with a magnet the mercury began to rotate around the wires.

All the apparatus which had been invented to try out the various ideas as they came along had been made individually for the express purpose of demonstrating single facts. Now Ampère began work on a new electrodynamic apparatus which could replace all the others (Gay Lussac and Arago 1824c). The apparatus was still clumsy by modern standards but nevertheles for its day, versatile. Basically it was a table on which were mounted some permanent conductors, a reversing switch and a compass galvanometer. To demonstrate the various facts there was provision for suspending the various horizontal, vertical or rotating wires. Figure 7 shows a version of this apparatus which is kept in Munich.

At last Ampère's chief and most celebrated work, *Memoir on the mathematical theory of electromagnetic phenomena uniquely deduced from experiment*, was published in 1827. This treatise was over two hundred pages long and was mainly derived from his announcements given to the *Institut* on December 4th and 26th 1820, June 10th 1822, December 22nd 1823, September 12th 1823 and November 21st 1825.

Tributes and conclusion

When Ampère finished his electrical studies he was 50 year old. From about this time he began to develop a chronic chest infection and his rheumatism became an ever increasing problem. Nevertheless he successfully competed for a teaching post at the famous *Collège de France*. Although this gave him some prestige it was a bad move as it meant a cut in salary. His sister, who kept the household budget, had run up debts of over 11 000 francs in order that he could carry on his electrical researches but all this expense had now to stop. Nevertheless Ampère continued to show interest in all sorts of scientific affairs. Besides his maintained interest in electricity he beame interested in Dulong's atomic heats as well as the new ideas on evolution which he strongly favoured.

In 1832–3 his health had become so bad that he was replaced at the *College* by Savart and Becquerel. He was at this time an inspector for the Paris university. It was on one of these journeys of inspection that he was taken ill in Marseilles. Too ill to return he remained there until his death on July 11th 1836. His remains were transferred to the Montmatre cemetary in 1869.

That Ampère was one of the giants of nineteenth century science there is no doubt. The theory of electromagnetism he had produced was quite extraordinary for its time and even today we regard a good proportion of it to be valid. It was only right that Helmholtz, at the meeting of the International Congress of Electricians held in Paris in 1881, should have favoured the word 'ampere' as the unit of electric current, even though the word 'weber' had been proposed.

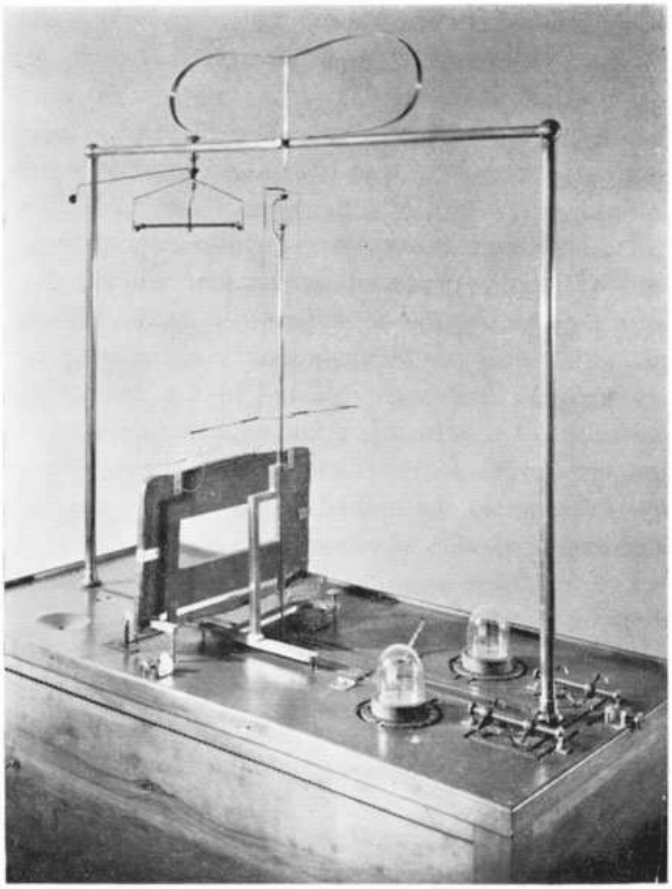

Figure 7 Ampère's 'general purpose' apparatus for carrying out electromagnetic experiments
(Photo: Deutsches Museum München).

On the centenary of Ampère's death the *Société des Amis d'André Marie Ampère* held a conference at which it received many good will messages and appraisals of Ampère's work from scientific societies all over the world. Perhaps then it is fitting to close this article with a quotation from one of these scrolls which was sent by our own *Physical Society* and which is still on display in the Museum at Poleymieux. 'The world owes much to the labours of him who has rightly been called the *Newton of Electricity:* and the work of the conference; concerned as it is with the developments which the genius of Ampère has made possible, is a fitting tribute to the memory of a great natural philosopher whose achievements (*monumentum aere perennius*) are honoured throughout the whole world of science.

(Signed) Rayleigh
President'.

Acknowledgments

I would like to thank the Perpetuel Secretaries of the *Académie des Sciences*, Robert Courrier and Louis de Broglie, for setting out some of the important events which took place at those hectic Monday meetings of the *Institut*. For her help with some of the most difficult translations I would like to thank my colleague Mlle Nadège Brunel. Finally I must express my appreciation to Robert Moïse, director of the Ampère Museum, and to the referees of this article for their help concerning certain technical points arising in the manuscript.

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